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RESEARCH MEMORANDUM

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RESEARCH MEMORANDUM

INVESTIGATION OF A CONTINUOUS NORMAL-SHOCK POSITIONING CONTROL ON THE BYPASS OF A SUPERSONIC INLET IN COMBINATION WITH THE J34 TURBOJET ENGINE

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SUMMARY

A normal-shock positioning control which utilized the bypass of a supersonic inlet to set the required air flow for a J34 turbojet engine was investigated to Mach number 2.0 in the Lewis 8- by 6-foot supersonic tunnel. A small static probe extending from the cowl was used to position the normal shock slightly ahead of the cowl lip and gave subcritical inlet operation. Continuous control was provided through a hydraulic servoactuator.

Continuous control without oscillations was obtained by use of the pressure signal from the small static probe. Calculated response time agreed reasonably with measured values. Experimentally determined control response required to avoid inlet pulsing due to engine imposed disturbances agreed reasonably with the computed value. A backward-facing total probe provided a more generally applicable control signal than the static probe used.

INTRODUCTION

The principles of positioning both the normal and the oblique shocks of supersonic inlets are presented and discussed in references 1 and 2. These principles were applied to an on-off system in reference 3 to control an inlet for a turbojet engine. The inlet spike was positioned to have the oblique shock fall slightly ahead of the cowl lip, and a bypass was positioned to obtain critical inlet operation.

Since matching studies indicate that for some turbojet applications maximum thrust minus drag occurs when the inlet is operated slightly subcritically, the work was extended in the present investigation to obtain subcritical inlet operation. In addition, continuous control of the bypass was provided.

The same J34 engine-inlet configuration of reference 3 was used, and tests were made at zero angle of attack at Mach numbers from 1.6 to 2.0 in the NACA Lewis 8- by 6-foot supersonic wind tunnel. Control response was investigated following manual displacements of the bypass from the control position. Additional disturbances on the system were obtained by suddenly reducing engine fuel flow and by firing rockets upstream of the inlet.

Steady-state pressure data for a backward-facing total probe investigated as an alternative means of determining normal-shock position are also discussed. 3863

APPARATUS AND PROCEDURE

The supersonic inlet used with the J34 engine had a translating 25° half-angle spike and an adjustable bypass which could spill as much as 20 percent of the engine air flow. Details of the inlet are given in reference 4. For the control data presented the spike was positioned to maintain the oblique shock slightly ahead of the cowl lip.

Engine fuel flow was controlled manually throughout the tests. A schematic diagram of the control system used on the bypass is shown in figure 1. A small static probe extending from the cowl lip was used to sense the normal-shock position. The probe was connected to a pressure transducer which was referenced to a static orifice on the spike surface 3 inches from the tip. The transducer voltage output was fed into a variable-gain direct-current amplifier. The amplifier voltage was compared with a reference voltage, and the resulting error voltage was used to operate a hydraulic servomechanism which actuated the bypass. Details of the backward-facing total probe are also given on the figure. Steady-state pressures only were obtained with this tube.

The bypass actuator was supplied with oil at a pressure of 1500 pounds per square inch and was regulated by a pilot valve. This valve was positioned by the error voltage so that the rate of bypass travel was proportional to error (servo input) voltage. Time for full travel of the bypass is plotted against input voltage in figure 2. Pilot valve position is closed at zero volt and full open at about 7 volts.

Figure 3 is a photograph of the normal-shock sensing probe which was located on the bottom of the cowl and for which the dimensions are given in figure 1. Two probes are shown, one of which was used with the control system and the other of which was connected to an automatic pressure recorder to record steady-state pressures.

Transient data were recorded by an optical-type oscillograph using transducers for pressures and slide-wire position indicators for the bypass and spike.

Dynamic behavior of the control was investigated by manually displacing the bypass from its controlled setting at the midposition to full open or full closed. Control response was measured for various gain settings of the transducer amplifier. In addition, the control was subjected to changes in engine fuel flow and to exhaust from a 2.75-inch air-to-air powder rocket fired 41 feet upstream of the inlet.

RESULTS AND DISCUSSION

The differential pressure available to operate the control is presented in figure 4 as a function of inlet corrected air flow. It was made nondimensional by dividing by ambient static pressure. The air flow is corrected to conditions ahead of the bypass (station 2, fig. 1). The data shown were taken with an exit plug replacing the engine in order to obtain extreme values of air flow. During the control tests the spike was always positioned to maintain the oblique shock slightly ahead of the cowl lip. Data are included in figure 4 for other spike settings to show the effect of oblique-shock position on the control signal. Also shown is the theoretical change in the pressure parameter calculated from shock theory.

At a free-stream Mach number of 2.0 (fig. 4(a)), a sharp rise in static-pressure parameter occurs as the inlet corrected air flow is reduced from a high value to a lower one. This is the condition at which the normal shock passes the static probe. The value of corrected air flow at which this happens varies with the amount of supersonic spillage and diffuser pressure recovery obtained with the various spike positions. The control setting used was selected to be approximately midway along the steep portion of the curve. For values of pressure parameter above the control setting, the bypass would open, and for values below, the bypass would close. Although the slope of the static-pressure parameter at the control point is very steep, it is not vertical. Moreover, the bypass that is being controlled discharges a maximum of only 20 percent of the total engine air flow.

With the spike position used for the control, a dip in the pressure-parameter curve coincident with the unstable inlet flow was observed. The sharp drop at a corrected air flow below 19 pounds per second for the oblique shock inside the cowl is due to the passage of the normal shock ahead of the cone reference orifice. In general, fair agreement between calculated and experimental values of static-pressure parameter was obtained when the normal shock was ahead of the probe. The poor agreement when the normal shock was behind the probe is attributed to three-dimensional flow effects and probe misalinement with the local flow.

The same trends exist at a free-stream Mach number of 1.8 (fig. 4(b)). At this Mach number, however, the normal-shock strength (and, consequently, the control signal) is noticeably reduced.

Data for Mach number 1.6 are presented in figure 4(c). Since at this Mach number a detached wave remained ahead of the cowl lip, a gradual rise in pressure parameter was obtained in going from supercritical to subcritical inlet operation. Because of the poor signal, the control was not operated at this Mach number.

Data points taken at Mach number 0.6 are also shown on this figure. At this Mach number the control would close the bypass, or if it were used to position the spike as in reference 3, the spike would be fully retracted. It is believed that the static-pressure parameter would remain close to zero for Mach numbers up to 1.33 (the Mach number at which an oblique shock attaches to the spike).

Data obtained with the backward-facing total probe are shown in figure 5. As would be expected with supersonic flow at the probe, the pressure measured was considerably lower than the local static pressure. Moreover, this type of probe appears less sensitive to misalinement with the flow than the static probe. Because of this fact and the location away from the cowl inner surface, the backward-facing probe provided a good control signal even at Mach number 1.6. Because the signal pressure drops below the reference pressure for supercritical conditions, it is possible to select a control setting at a static-pressure parameter of zero. In this case any need to correct the control setting for changes in altitude is avoided. With this setting, however, the control would be inoperative at subsonic speeds. In order to obtain the proper control action at subsonic speeds, the control setting must be either above or below zero.

Steady-state operating points set by the control for various engine speeds are superimposed on diffuser performance curves (fig. 6) obtained from bypass-closed data. The data indicate that, as intended, the control set slightly subcritical inlet operation (not necessarily the optimum thrust minus drag for this inlet). A narrow margin of stable operation was obtained at Mach number 2.0 (fig. 6(a)) between the point set by the control and the region of unstable flow. No unstable operation of the inlet was obtained at Mach number 1.8.

Schlieren photographs in figure 7 show the slightly subcritical positioning of the shock during control operation at Mach numbers 2.0 and 1.8, respectively. The normal shock is at the location of the probe orifice at Mach number 2.0 and slightly ahead at Mach number 1.8. The inlet mass-flow ratio set by the control for Mach number 1.8 (fig. 6(b)), however, was only slightly less than the critical value.

Control response data obtained by displacing the bypass full open or full closed from the control point of half open is presented in figure 8. Response time is defined as the time required for the control to restore the bypass 90 percent from its displaced position. The control response time decreased with increasing sensor gain to a value approaching that for minimum possible response time or full open position of the pilot valve. Calculated response was obtained by using the static-pressure parameters from figure 4 which would be obtained at the displaced condition, converting the pressure signal to volts, and using figure 2 to obtain the response. In calculating the response in this way, it is assumed that a constant error signal is obtained until the shock reaches the control point and then the error signal drops to zero. The slow action of the servoactuator relative to the other system lags permits this calculation to be made. Reasonable agreement is obtained between calculated and experimental response. Control oscillation, as distinguished from inlet instability, was not obtained until sensor gains resulting in nearly minimum possible response were used.

A typical trace of control operation for a manually displaced subcritical operating point is shown in figure 9(a). The inlet pulsed during the time the door was held closed as can be seen from the compressor-inlet static-pressure trace p_3. (All symbols are defined in appendix A.) When the control was turned on, it opened the bypass at a constant rate except for some lost time due to reversals in error signal when the pulsing normal shock passed behind the probe. It is seen from the signal voltage trace that during pulsing the normal shock is ahead of the probe for a much greater time than behind the probe. For this trace about 0.06 second out of a total response time of 0.22 second was lost because of pulsing. The amplitude of the pulsing, as shown on the p_3 trace, decreased as the bypass opened and damped out after about 3 cycles. Response time was 0.22 second with very little overshoot. The initial and final inlet operating points are plotted on the inlet performance curve in the lower part of the figure.

A trace in which the bypass was displaced open and supercritical operation resulted is shown in figure 9(b). Control action is shown by the long arrow on the diffuser performance curve in the lower half of the figure. The overshoot into the subcritical region shown is the maximum obtained during the tests and appears to be due to a combination of dead time and lag of normal-shock movement behind the engine deceleration rather than lag in control action. It can be noted that the control did not receive an error signal to reverse the bypass direction until the overshoot had reached a maximum. The amount of overshoot indicated on the inlet performance curve of figure 9(b) was calculated from steady-state data of bypass air flow. The fact that the inlet did not pulse during the overshoot period suggests that because of lag in normal-shock movement the calculation based on steady-state air flow may not be applicable. It is also possible that pulsing did not start because of the short time in the unstable operating region. Following the overshoot, the bypass position settled out slightly more closed than its original half-open position because of a rise in engine speed during the time inlet operation was supercritical.

Control overshoot for manual displacement of the bypass is a rather complex function of amplifier gain combined with change in engine speed. The engine-speed change will depend on the length of time the bypass was held displaced and upon how much the diffuser pressure recovery was decreased by the displacement. The amount of engine-speed change should be greater for supercritical than for subcritical displacement because of the greater decrease in diffuser pressure recovery. It should be emphasized that for these transient studies the engine fuel flow was manually controlled and maintained at a constant value during the transient.

In figure 10 control overshoot is presented in terms of percentage of inlet air flow. Overshoot is seen to be greater for supercritical than for subcritical displacement. The maximum amount of slightly over $4\frac{1}{2}$ percent was obtained for supercritical displacement (bypass open) at Mach number 2.0 (trace on fig. 9(b)). 3863

The maximum continued oscillation obtained with the control is shown on figure 11. Frequency was 10 cycles per second, and the amplitude corresponded to about 1.7 percent of the inlet air flow. The amplitude of oscillation was limited by the dynamics of the hydraulic actuator. The steady compressor-inlet static pressure on the trace indicates that engine operation would be little affected by control oscillation. Response time was greater for this trace than for the trace of figure 9(b) because of the lower free-stream Mach number. This lower Mach number resulted in a weaker normal shock and thus a lower error signal.

Disturbances were applied to the control by suddenly changing engine fuel flow to determine how fast the control must be to avoid inlet pulsing caused by engine imposed disturbances. Figure 12 is a reproduction of a trace of control action at Mach number 2.0 in which the engine fuel flow was reduced from 2410 to 1110 pounds per hour in 0.2 second. This fuel change would decelerate the engine sufficiently to put the inlet into severe pulsing if no action were taken by the control. The sensor gain used of 0.0014 volt per pound per square foot was experimentally determined to be approximately the minimum gain at which pulsing could be avoided for this fuel disturbance. No inlet pulsing was observed on the trace. The required sensor gain was calculated to be 0.0017 volt per pound per square foot (see appendix B). The resulting calculated rate of bypass travel is included on the figure. The difference of about 0.2 second between the calculated and experimentally observed curves of bypass movement is attributed to lag in shock movement not considered in the calculation. Also indicated on the figure is the calculated time at which the maximum deviation from the control point occurred.

One other disturbance applied to the control was that of firing a powder rocket 41 feet ahead of the cowl inlet with the tunnel at Mach number 2.0. During the 2-second duration of the rocket blast the inlet temperature increased and the normal shock oscillated violently. Although the control acted to move the bypass in the proper direction, the response was slow in comparison with the rapid rise in inlet temperature and little benefit was obtained. When the rocket propellant was consumed, the inlet temperature immediately dropped and the control restored stable inlet operation.

SUMMARY OF RESULTS

From an investigation of a turbojet engine-inlet installation in the Lewis 8- by 6-foot supersonic tunnel at Mach numbers of 1.8 and 2.0 with continuous normal-shock control of a bypass, the following results were obtained:

1. With the use of a pressure signal from a small static probe at the cowl lip, the control set peak inlet pressure recovery and, as intended, mass flow slightly less than the maximum value.

2. The time required for the control to correct manually displaced bypass positions agreed with calculated values.

3. Experimentally determined control response required to avoid inlet pulsing due to engine imposed disturbances agreed reasonably with the computed value.

4. A backward-facing total probe was shown to provide a more generally applicable control signal than the static probe used.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, October 10, 1955

APPENDIX A

SYMBOLS

The following symbols are used in this report:

A_f flow area at compressor inlet, 1.98 sq ft

m inlet mass flow, slugs/sec 3863

P total pressure

p static pressure

T total temperature

w inlet air flow, lb/sec

δ total pressure divided by NACA standard sea-level absolute pressure

θ total temperature divided by NACA standard sea-level absolute temperature

θ_l angle between inlet axis and line from spike tip to cowl lip, deg

Subscripts:

b backward-facing total

c cone

p cowl-lip probe

0 free stream

1 cowl lip

2 air-flow rakes ahead of bypass

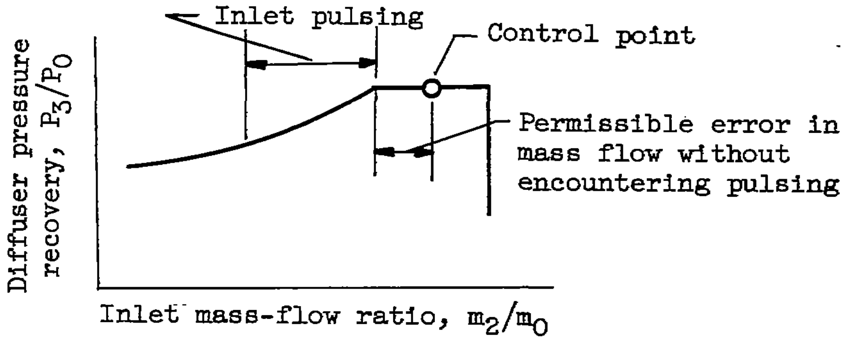
3 diffuser exit or compressor inlet

APPENDIX B

CALCULATION OF MINIMUM SENSOR GAIN REQUIRED TO AVOID INLET PULSING DUE TO ENGINE IMPOSED DISTURBANCES

The following calculation applies only to the control system used and to an inlet having a stable operating region of constant total-pressure recovery between the control point and the onset of pulsing. No allowance is made for any lag of the shock movement behind the deceleration of the engine.

Because of the stable region obtained with the inlet used, some error in the controlled diffuser air flow can be tolerated without encountering pulsing. This permissible error is illustrated in the following sketch of inlet performance:



If a disturbance is introduced, which causes the engine to decelerate, the corrected engine air flow is reduced. If the control increases the bypass air flow as fast as the engine air flow decreases, no error in inlet mass flow will be obtained. However, the subcritical stable margin of this particular inlet makes it possible to avoid pulsing with a control sensor gain that allows the bypass air-flow correction to lag the change in engine air flow.

Change in engine air flow. - It has been shown that a turbojet engine behaves as a linear first-order system in response to fuel disturbances. For the engine used, the variation of corrected air flow with engine speed was also linear. The variation of engine air flow in response to a step change in fuel flow is then given by

$$\Delta w_e = \Delta w_{e,eq}\left(1 - e^{-t/\tau}\right) \tag{1}$$

where

Δw_e change in engine air flow from initial value at time t, lb/sec

$\Delta w_{e,eq}$ change in engine air flow from initial value at equilibrium conditions, lb/sec

t time following fuel disturbance, sec

τ engine time constant, sec

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Change in bypass air flow. - The operating signal for the shock positioning control used was assumed to be constant for shock positions ahead of the probe (i.e., for cases where an error occurs). This assumption results in a constant rate of change of bypass air flow, the value depending on the control sensor gain. The change in bypass air flow is then

$$\Delta w_b = \left[\frac{dw_b}{dt} = k\right] t \tag{2}$$

where

Δw_b change in bypass air flow from initial value, lb/sec

$\frac{dw_b}{dt} = k$ rate of change of bypass air flow, (lb/sec)/sec

Error in controlled mass flow. - The error in controlled mass flow is the difference between change in engine air flow and change in bypass air flow.

$$E = \Delta w_e - \Delta w_b = \Delta w_{e,eq}\left(1 - e^{-t/\tau}\right) - \left[\frac{dw_b}{dt} = k\right] t \tag{3}$$

where

E instantaneous error in controlled air flow, lb/sec

Differentiating equation (3) to solve for a maximum yields

$$\frac{dE}{dt} = \frac{\Delta w_{e,eq}}{\tau} e^{-t/\tau} - \left[\frac{dw_b}{dt} = k\right] \tag{4}$$

A maximum error occurs at time t given by

$$t = -\tau \ln \frac{dw_b}{dt} \frac{\tau}{\Delta w_{e,eq}} \tag{5}$$

Substituting equation (5) into equation (3) gives the maximum error as

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$$E_{max} = \Delta w_{e,eq} - \tau \frac{dw_b}{dt} + \tau \frac{dw_b}{dt} \ln \frac{\tau}{\Delta w_{e,eq}} \frac{dw_b}{dt} \tag{6}$$

From figure 4(a) the controlled corrected air flow at $M_0 = 2.0$ and $\theta_l = 42$ is 26.1 pounds per second, whereas the corrected air flow at the onset of pulsing is 25.4 pounds per second. These values give an approximate permissible error E_{max} of 0.7 pound per second.

For the trace of figure 12 the change at equilibrium in engine air flow $\Delta w_{e,eq}$ corresponding to the fuel-flow step was 3.08 pounds per second. The value of τ observed from the trace was 0.7 second. Solving equation (6) gives the required rate of change of bypass air flow dw_b/dt as 1.80 pounds per second per second. From equation (5) the time at which the maximum error occurs is 0.625 second.

Calculation of required sensor gain. - The bypass corrected air flow for full-open bypass position was 5.78 pounds per second for the diffuser pressure recovery for figure 12. The response-time data of figure 8 are for 90 percent of half travel of the bypass. Bypass air flow for this amount of travel is thus (0.90)(0.5)(5.78) = 2.60 pounds per second. Since the required rate of change is 1.80 pounds per second per second, the response time for 45 percent travel is 2.60 ÷ 1.80 or 1.45 seconds. The value of sensor gain for Mach number 2.0 giving this response time is 0.0017 from figure 8.

REFERENCES

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2. Wilcox, Fred A., and Hearth, Donald P.: Application of Oblique-Shock Sensing System to Ram-Jet Engine Flight Mach Number Control. NACA RM E54L22a, 1955.

3. Leissler, L. Abbott, and Nettles, J. Cary.: Investigation to Mach Number 2.0 of Shock-Positioning Control System for a Variable-Geometry Inlet in Combination with a J34 Turbojet Engine. NACA RM E54I27, 1954.

4. Nettles, J. C., and Leissler, L. A.: Investigation of Adjustable Supersonic Inlet in Combination with J34 Engine up to Mach 2.0. NACA RM E54H11, 1954.

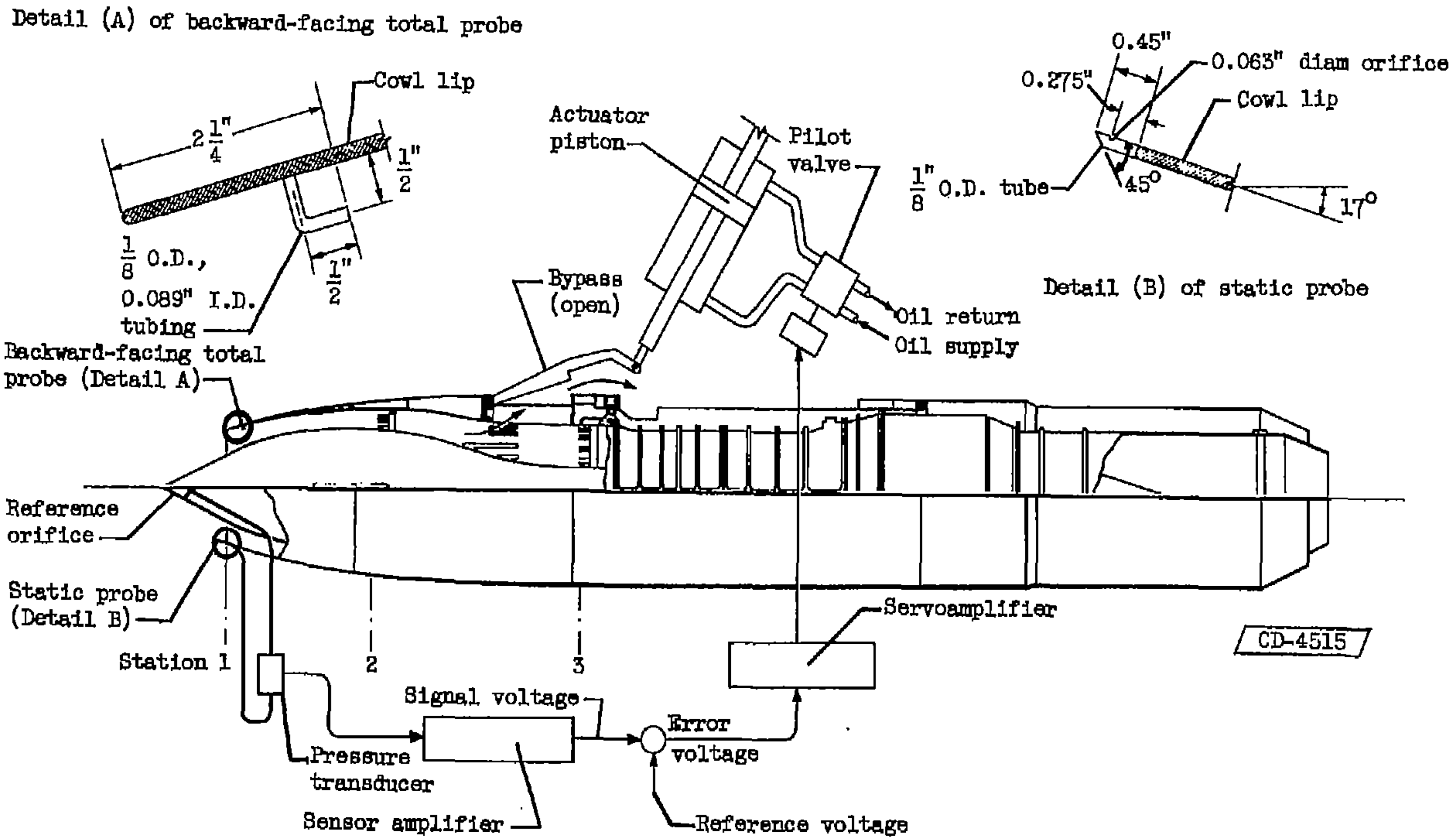

Figure 1. - Schematic diagram of control system.

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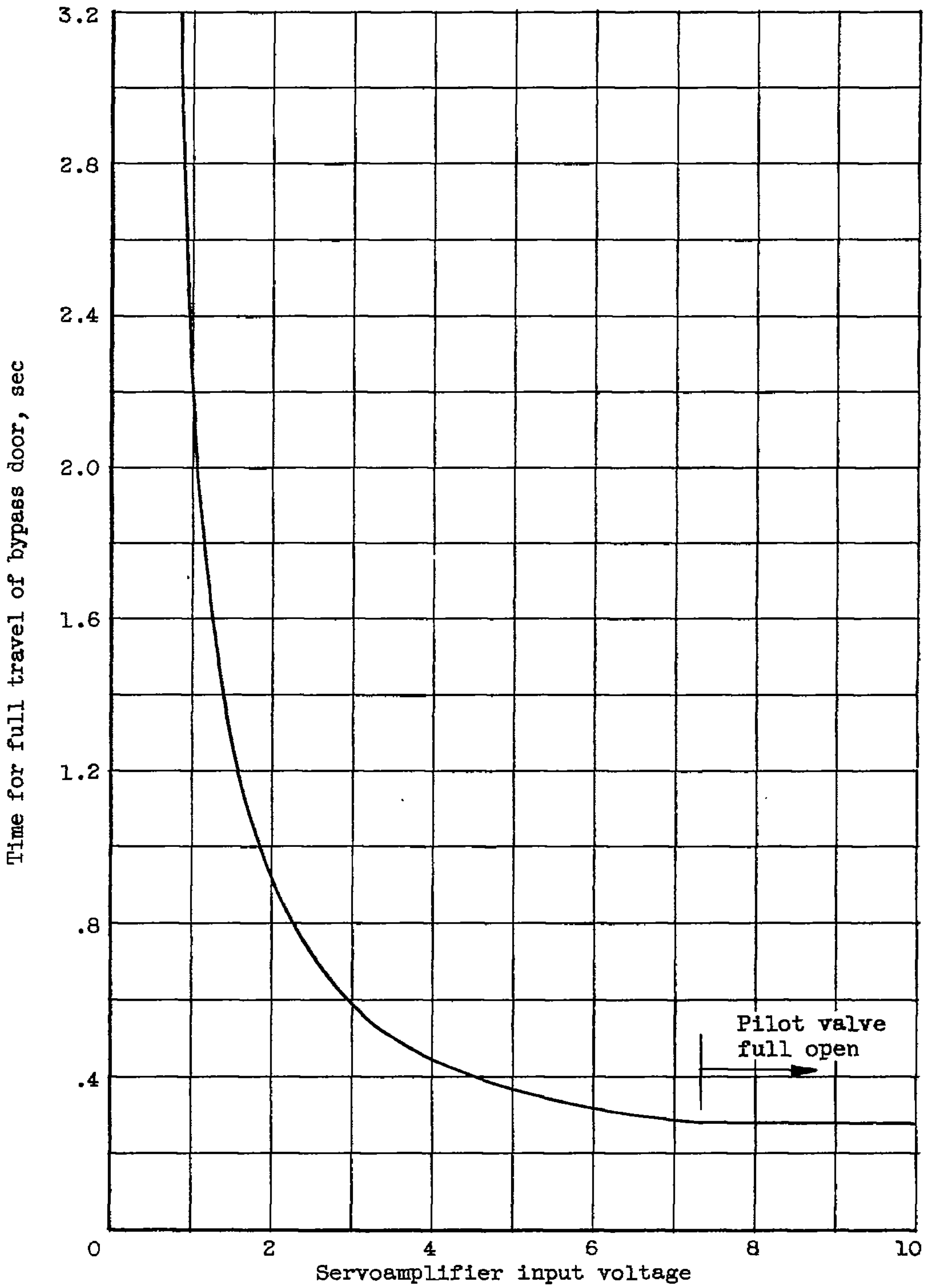

Figure 2. - Time for full travel of hydraulic servoactuator.

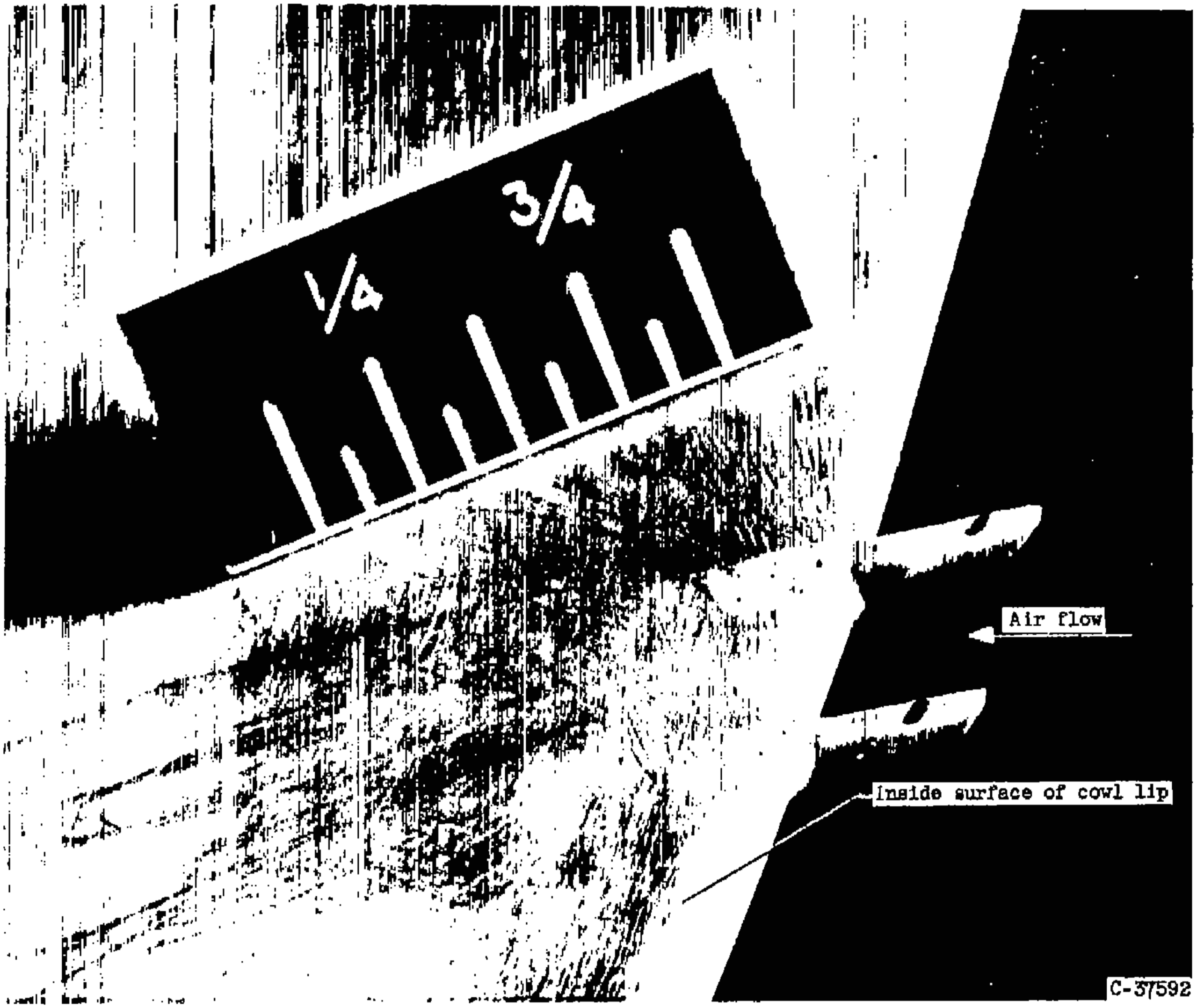

Figure 3. - Shock-sensing static probe.

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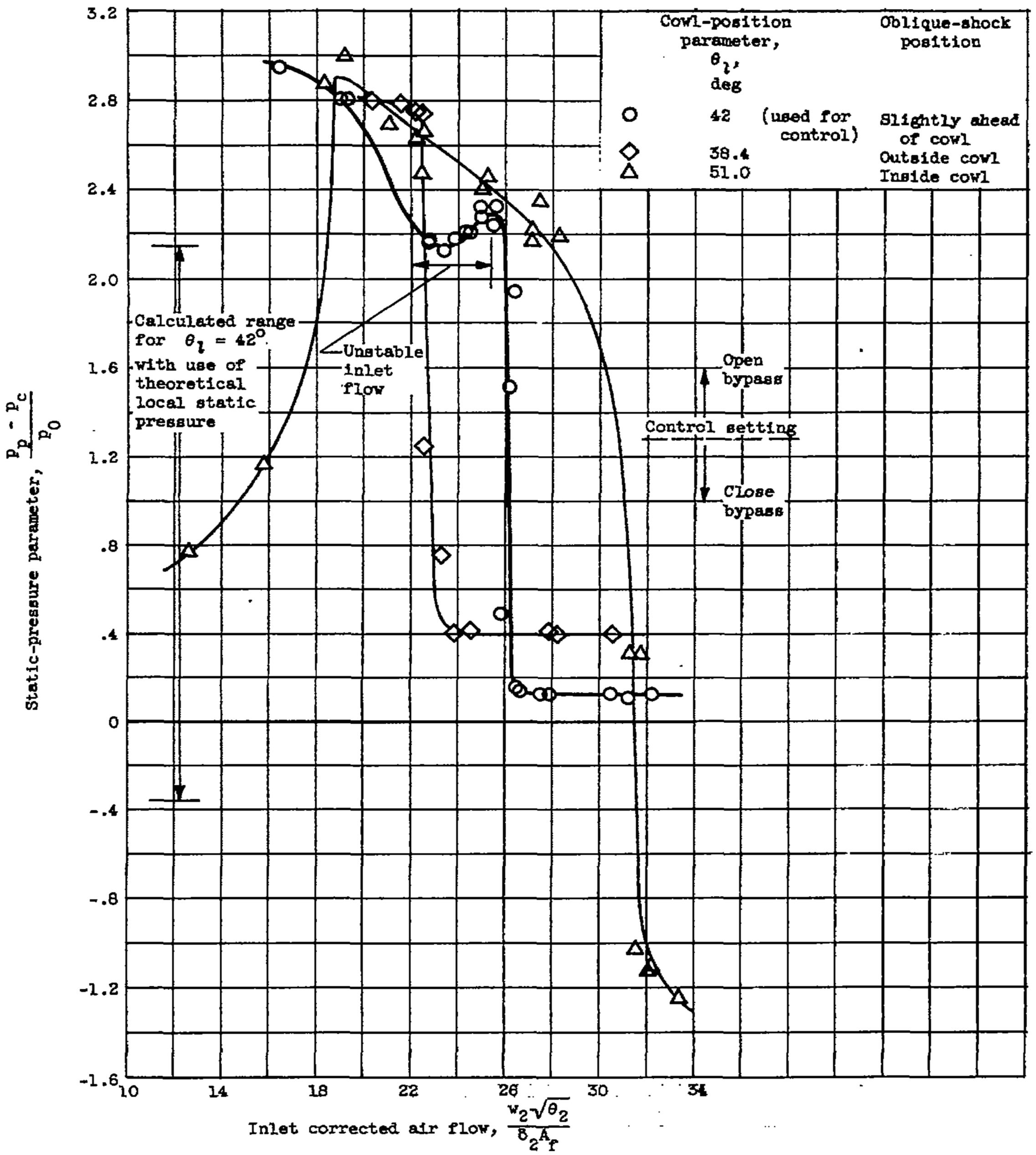
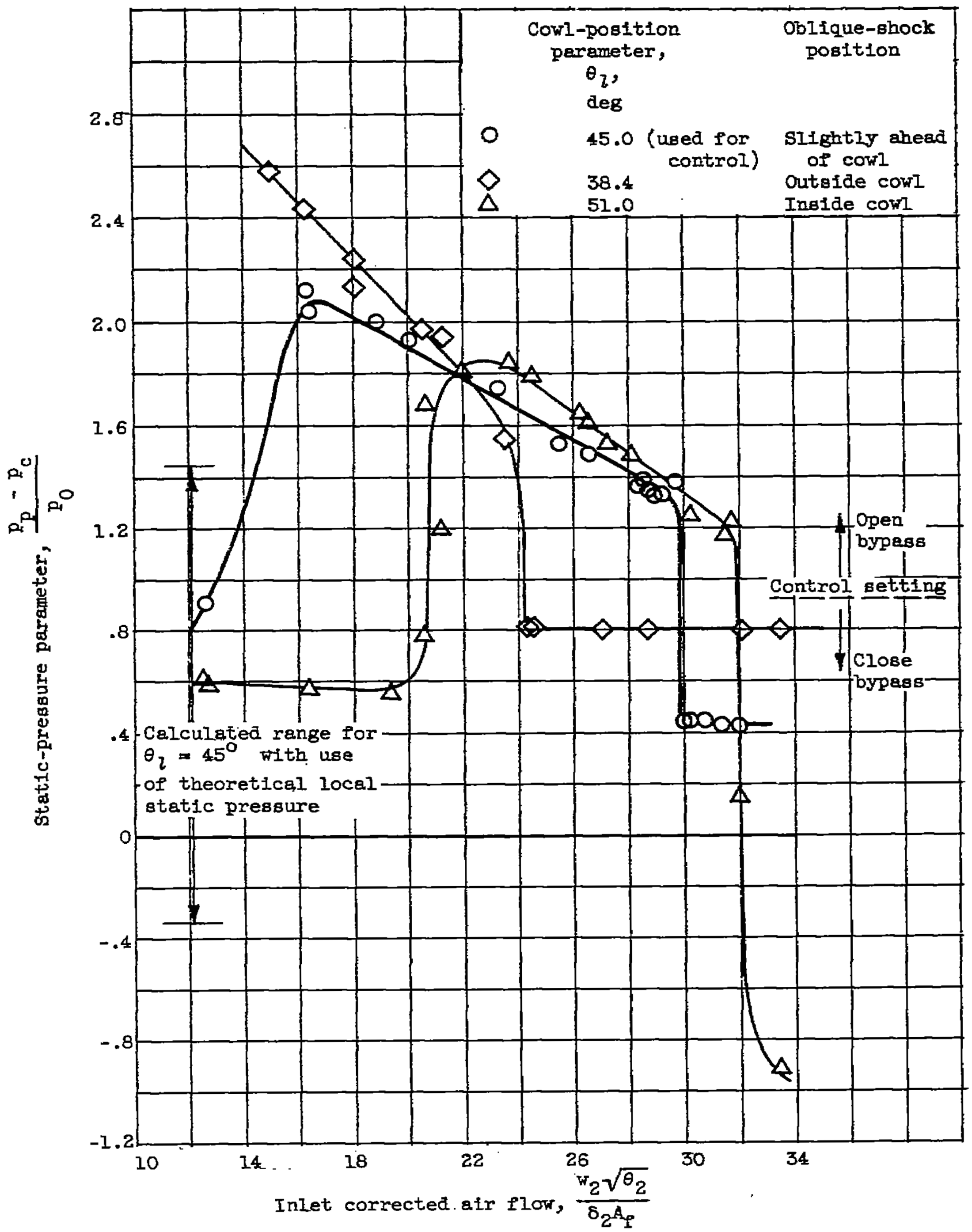


(a) Free-stream Mach number, 2.0.

Figure 4. - Variation of static-pressure parameter for shock-sensing probe.



(b) Free-stream Mach number, 1.8.

Figure 4. - Continued. Variation of static-pressure parameter for shock-sensing probe.

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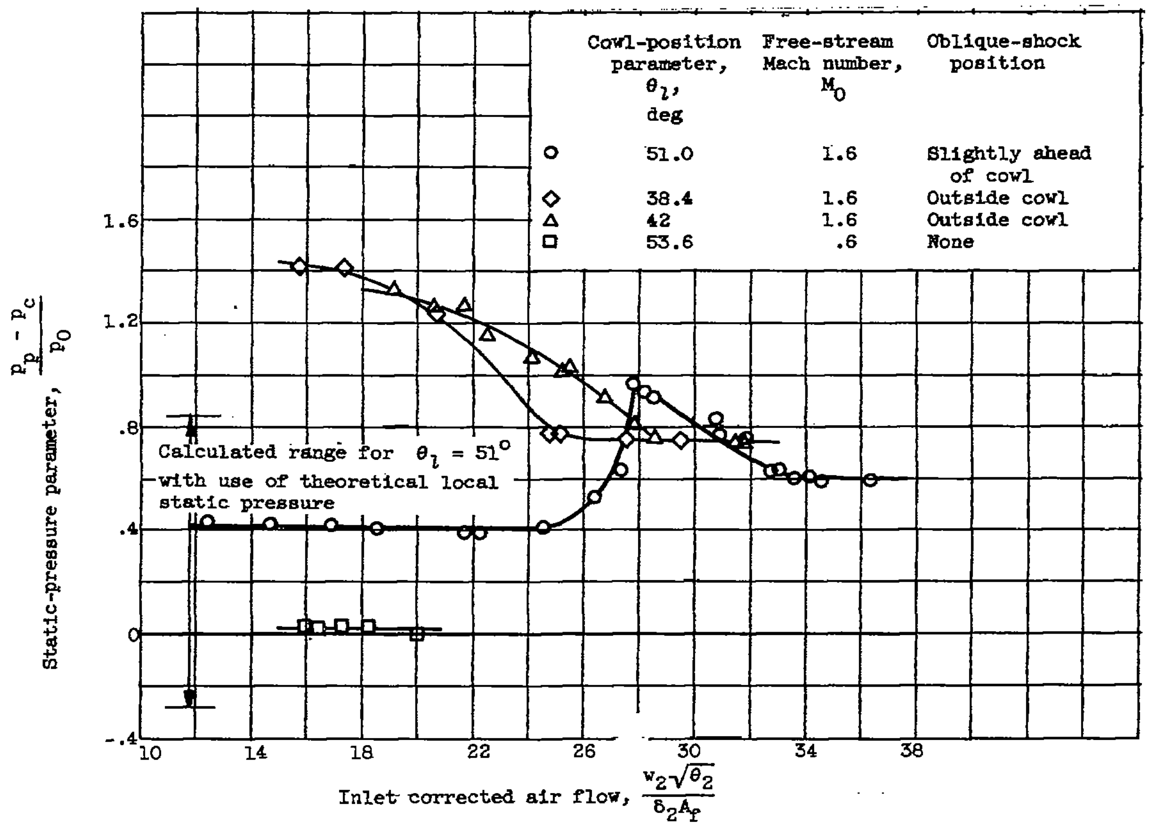
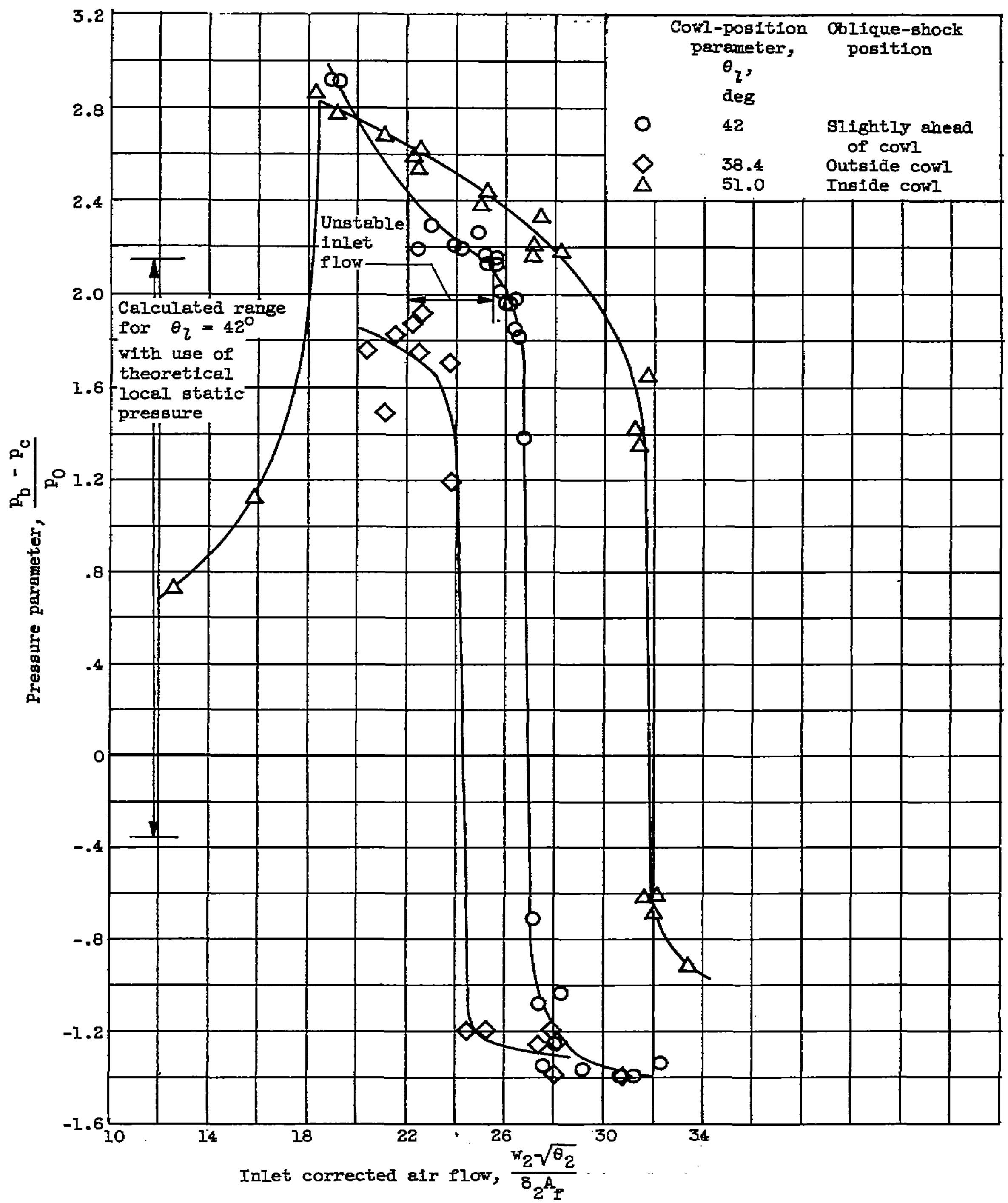


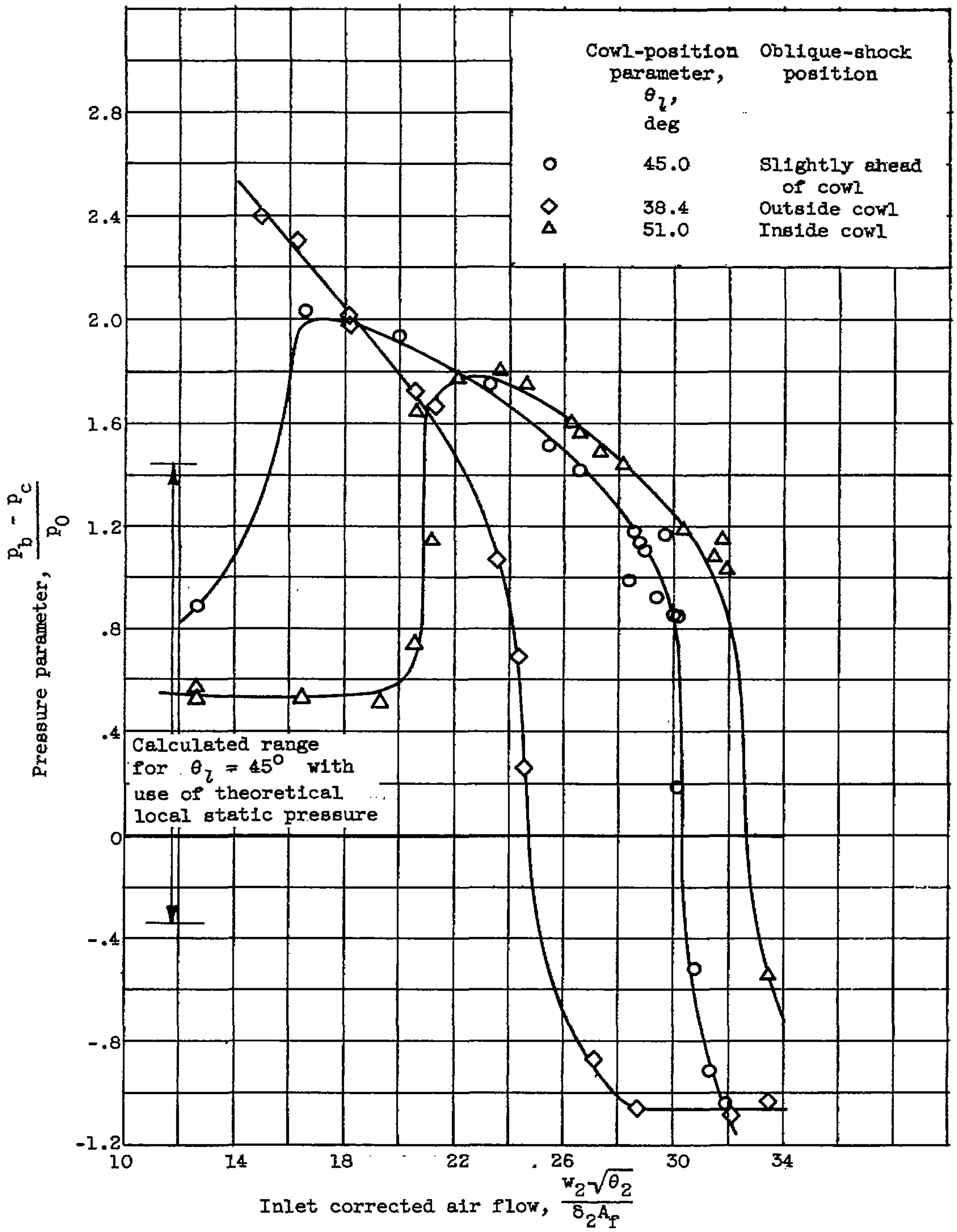
(c) Free-stream Mach numbers, 1.6 and 0.6.

Figure 4. - Concluded. Variation of static-pressure parameter for shock-sensing probe.



(a) Free-stream Mach number, 2.0.

Figure 5. - Variation of pressure parameter for backward-facing total probe.



(b) Free-stream Mach number, 1.8.

Figure 5. - Continued. Variation of pressure parameter for backward-facing total probe.

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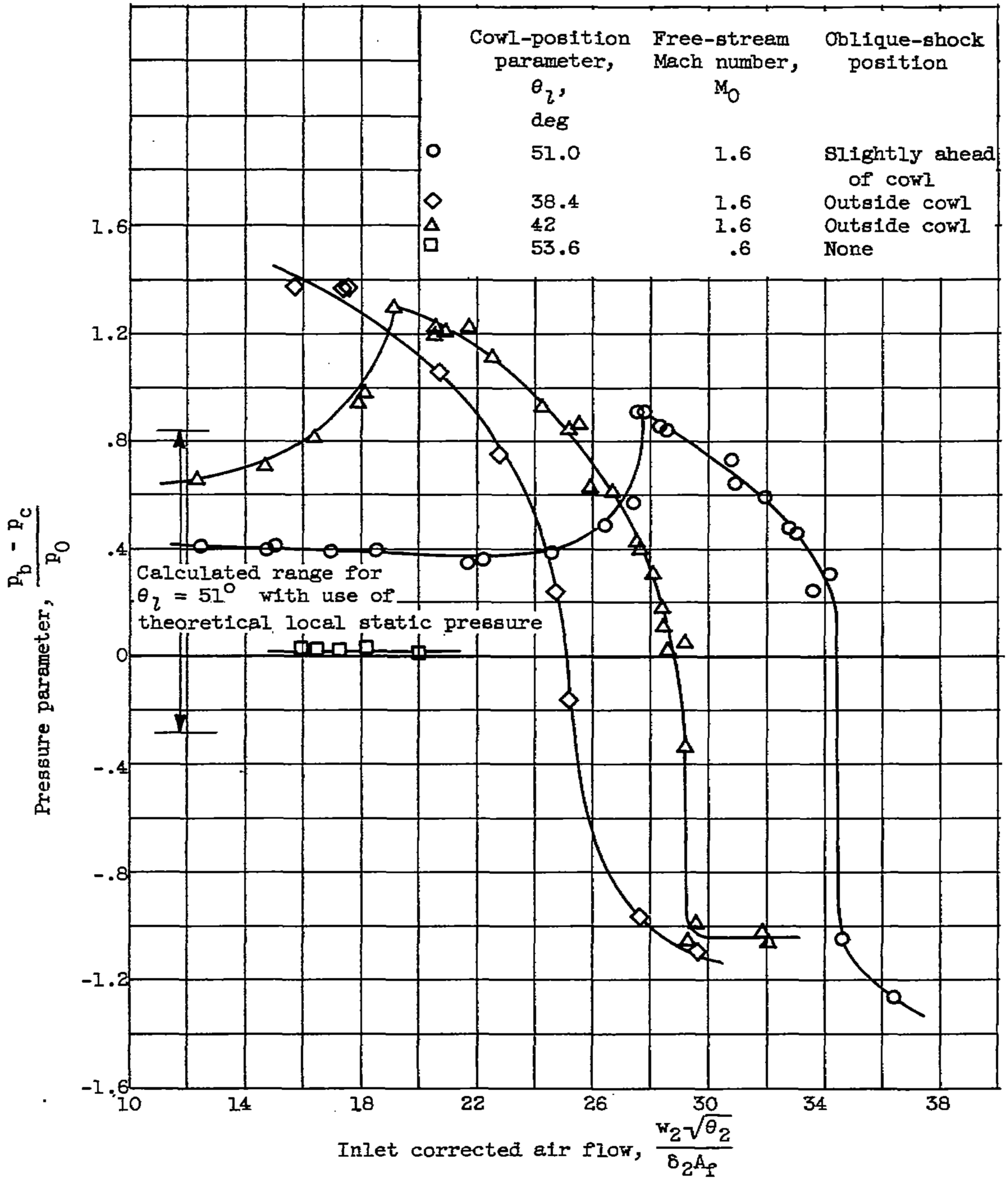

(c) Free-stream Mach numbers, 1.6 and 0.6.

Figure 5. - Concluded. Variation of pressure parameter for backward-facing total probe.

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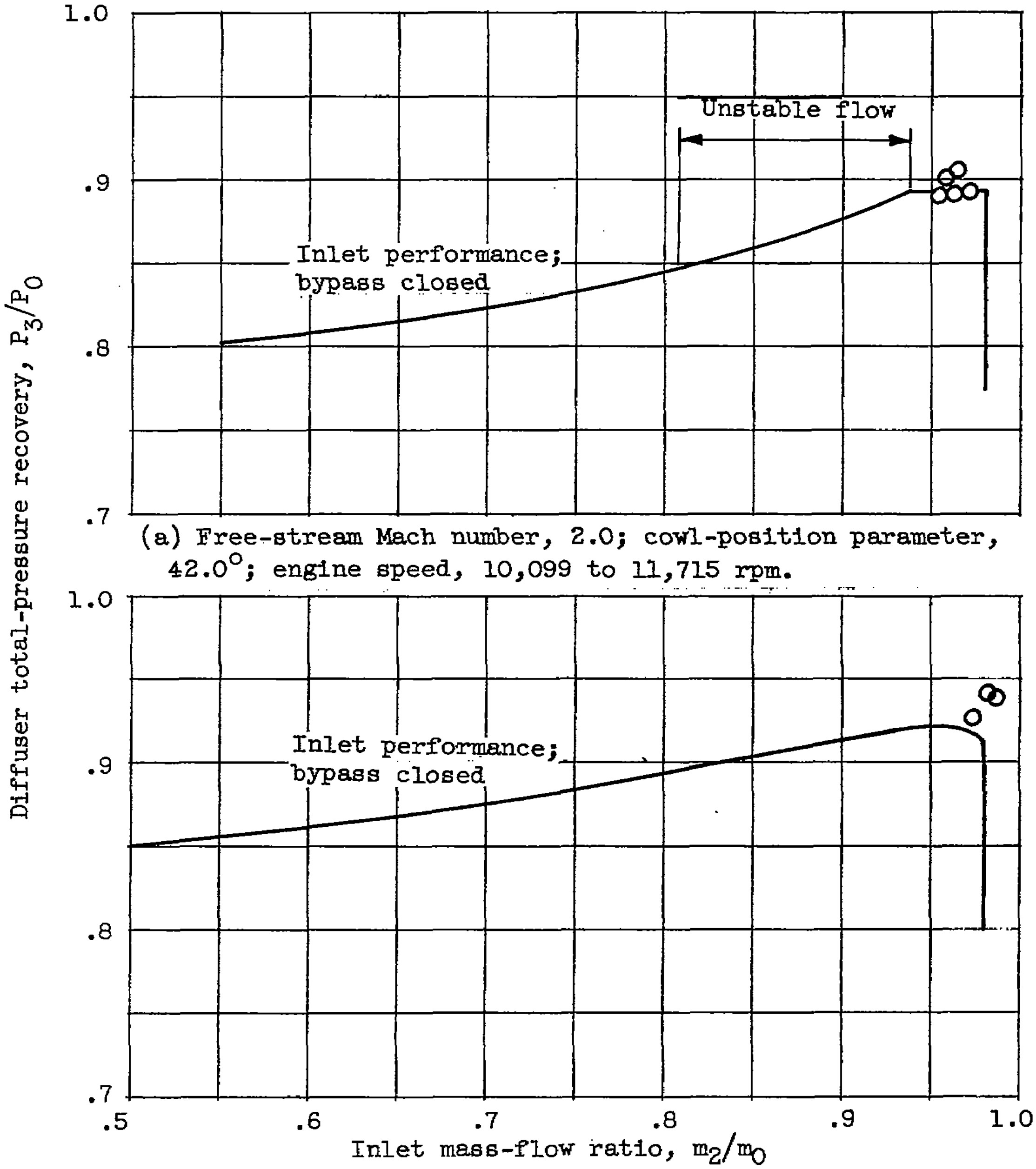

(a) Free-stream Mach number, 2.0; cowl-position parameter, 42.0°; engine speed, 10,099 to 11,715 rpm.

(b) Free-stream Mach number, 1.8; cowl-position parameter, 45.0°; engine speed, 11,028 to 12,018 rpm.

Figure 6. - Steady-state points set by control.

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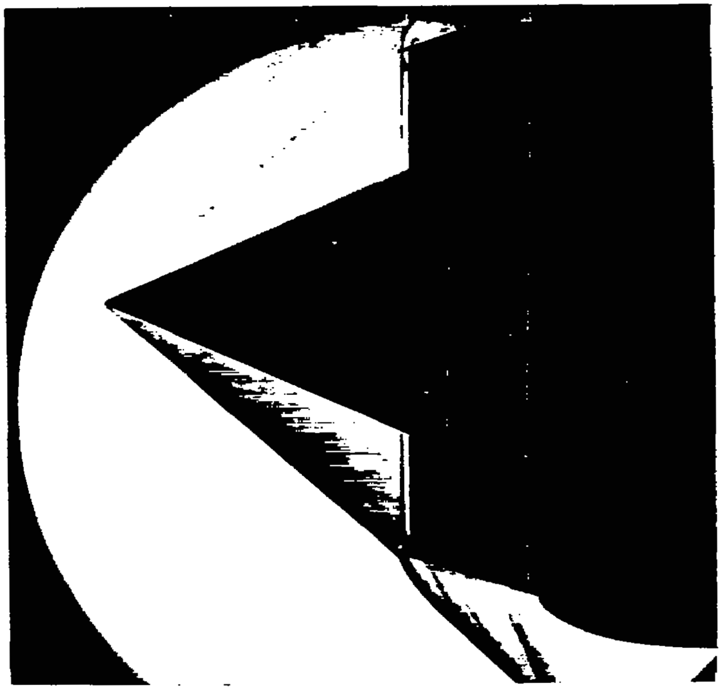
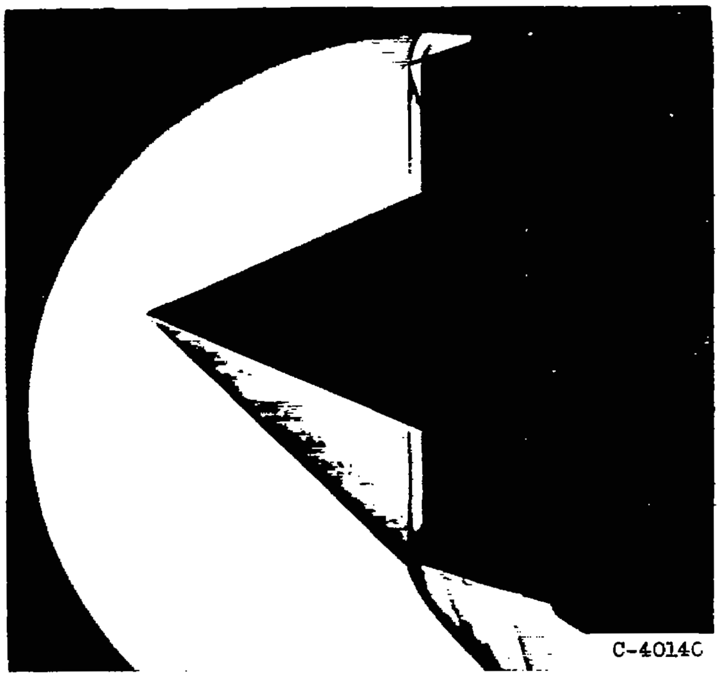


(a) Free-stream Mach number, 2.0.



(b) Free-stream Mach number, 1.8.

Figure 7. - Schlieren photographs of shock configuration set by control.

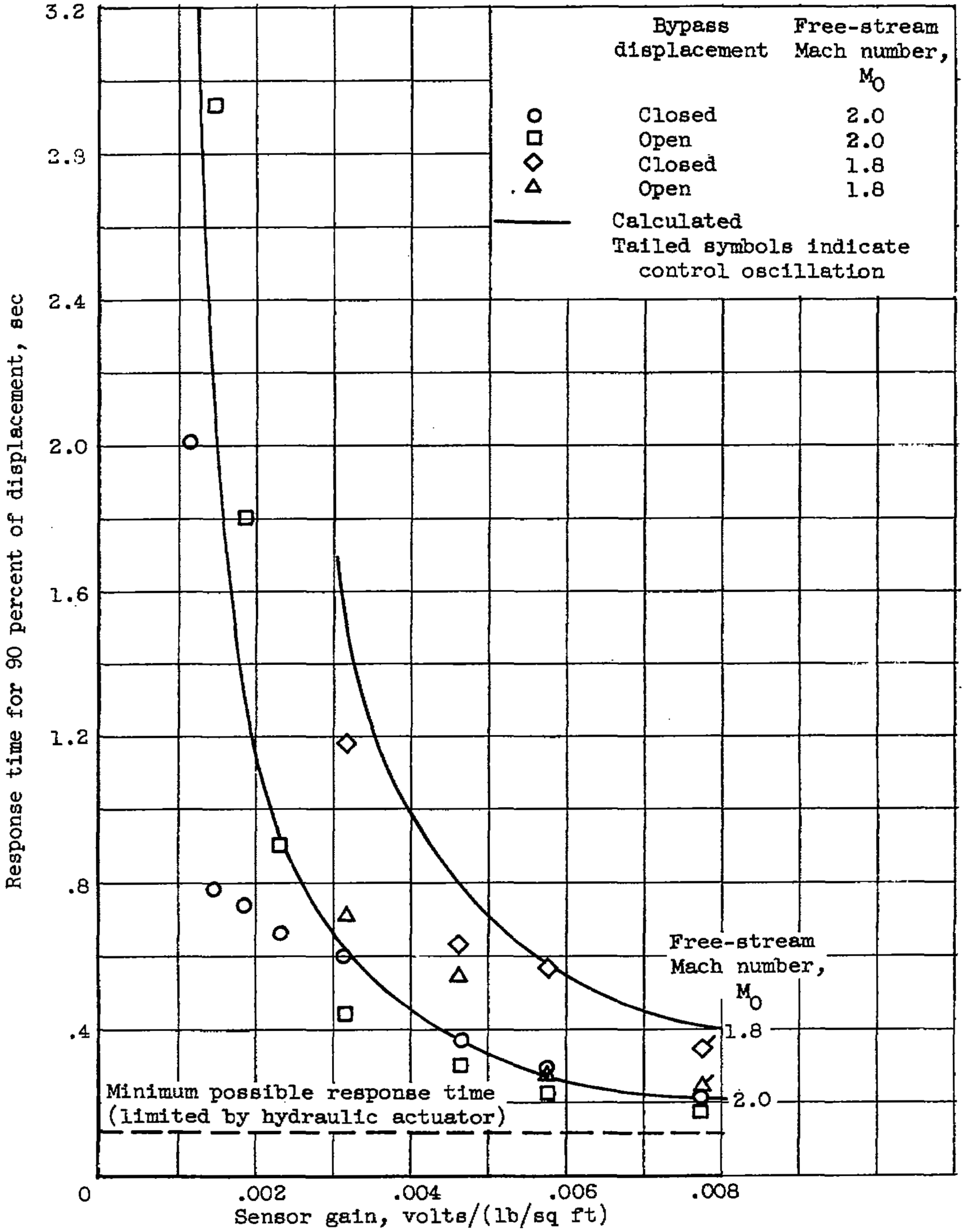


Figure 8. - Control response time for bypass displaced half of full travel.

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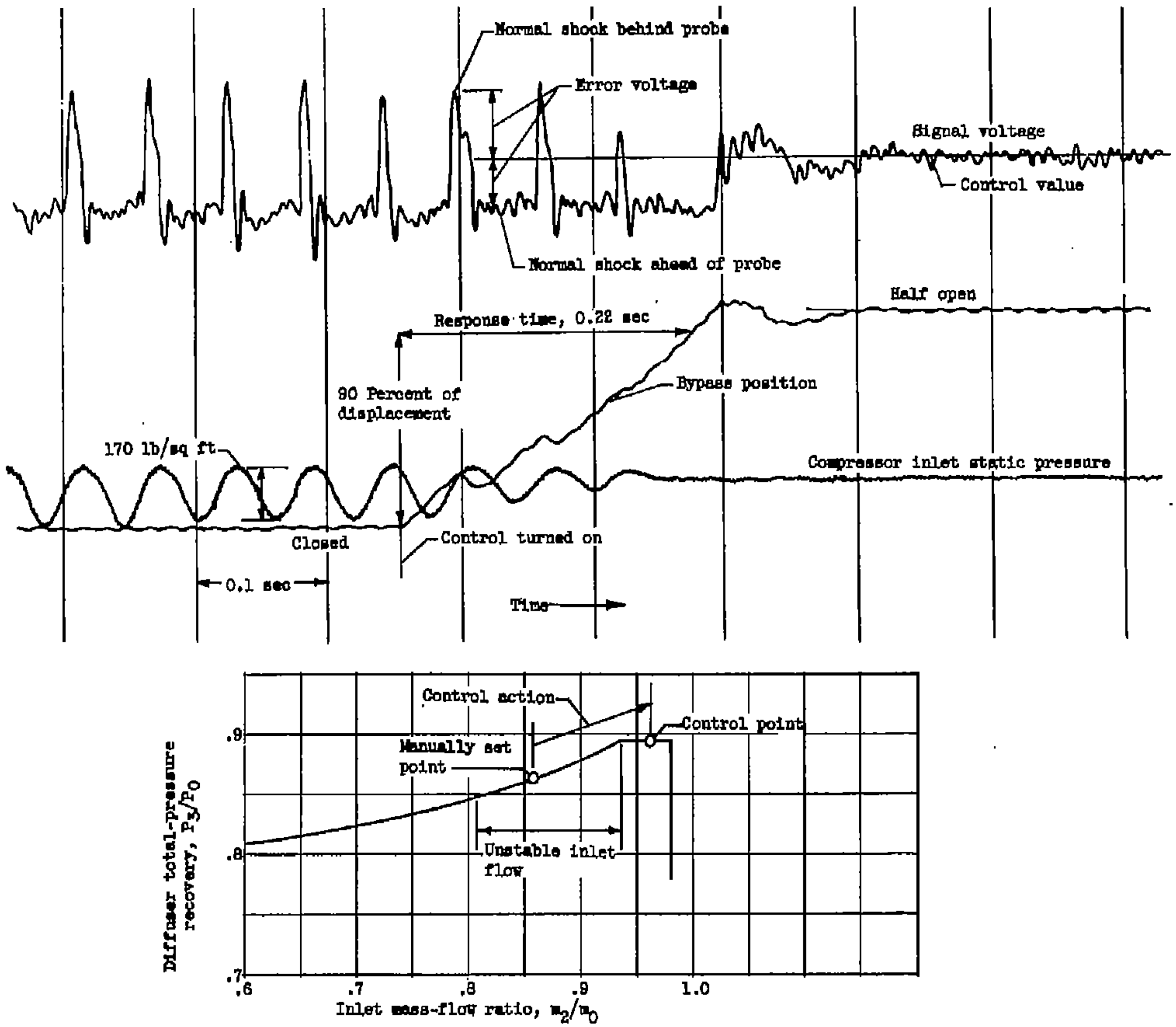
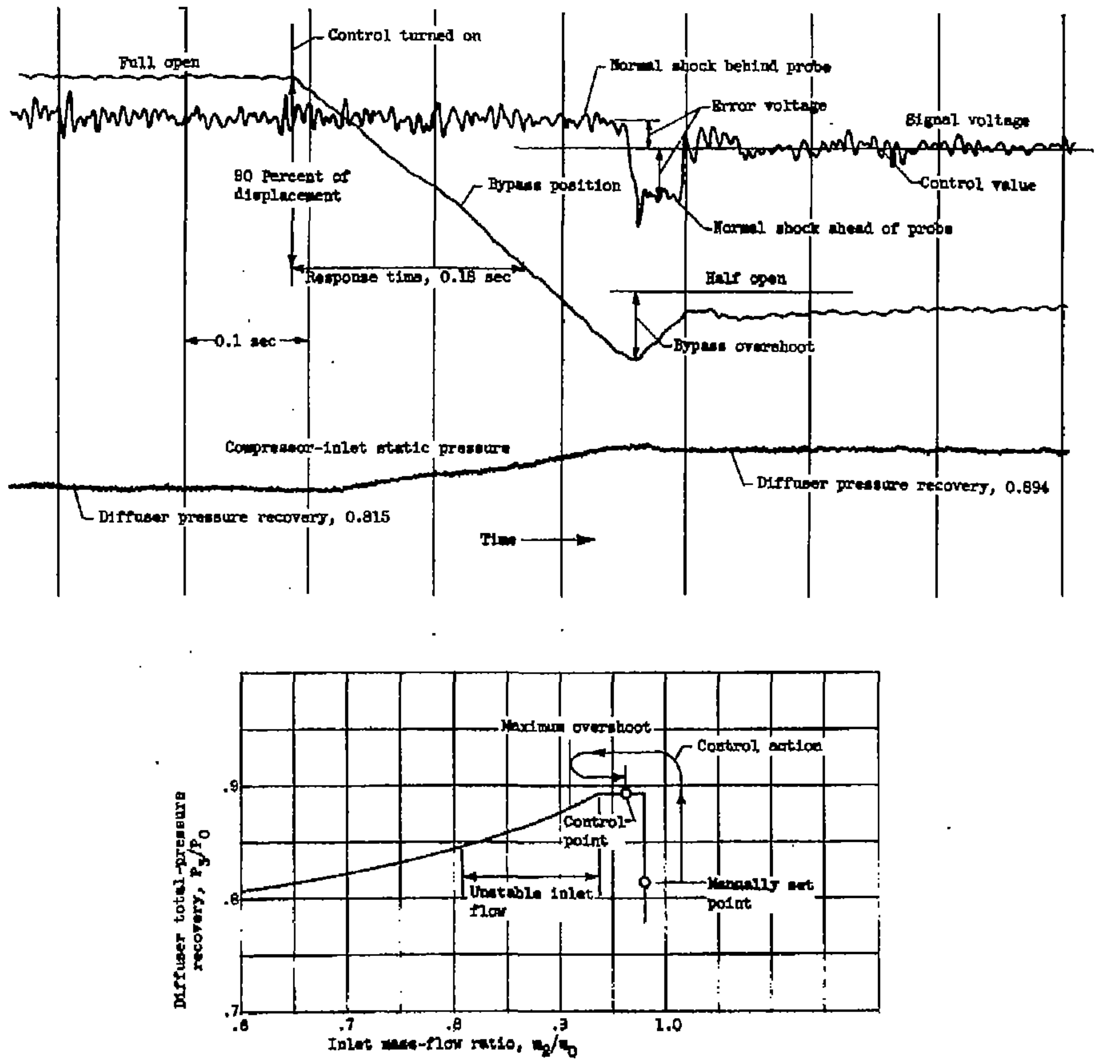


(a) Manually displaced subcritical operating point.

Figure 9. - Operation of control. Mach number, 2.0; cowl-position parameter, 42.0°; sensor gain, 0.0077 volt per pound per square foot.



(b) Manually displaced supercritical operating point.

Figure 9. - Concluded. Operation of control. Mach number, 2.0; cowl-position parameter, 42.0°; sensor gain, 0.0077 volt per pound per square foot.

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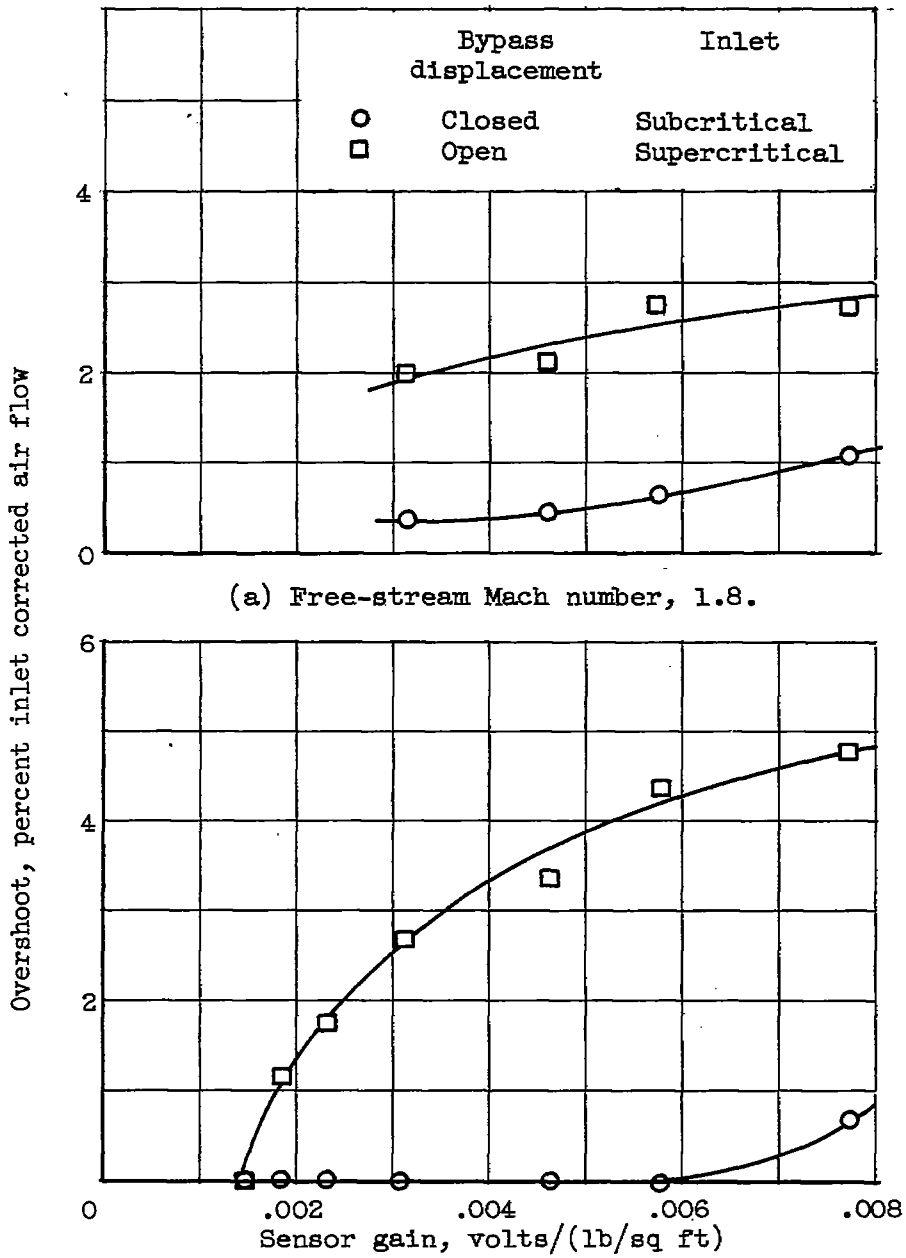

(a) Free-stream Mach number, 1.8.

(b) Free-stream Mach number, 2.0.

Figure 10. - Control overshoot for bypass displaced half of full travel.

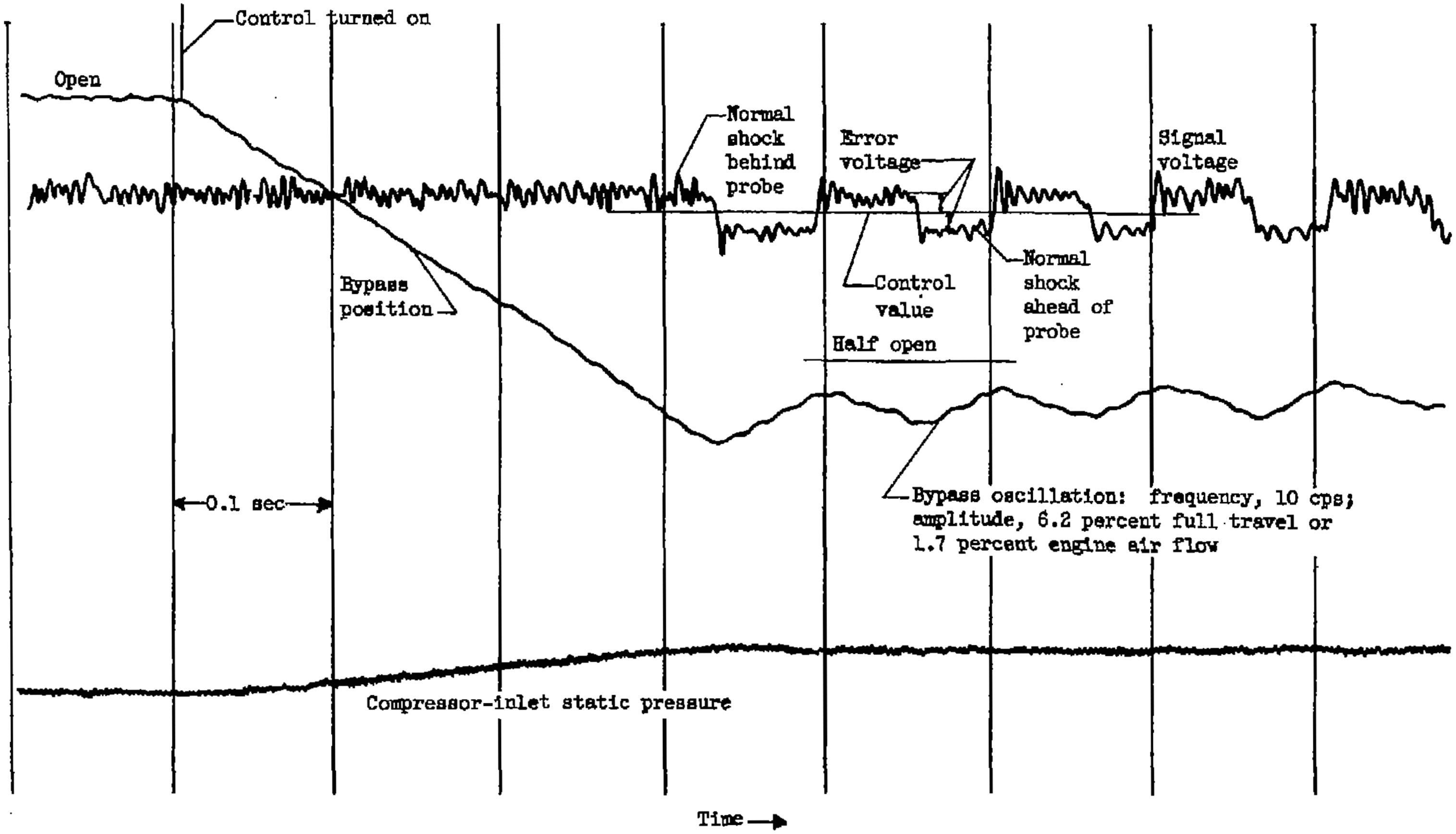

Figure 11. - Control oscillation following correction of manually opened bypass from initial half-open position. Free-stream Mach number, 1.8; sensor gain, 0.0077 volt per pound per square foot.

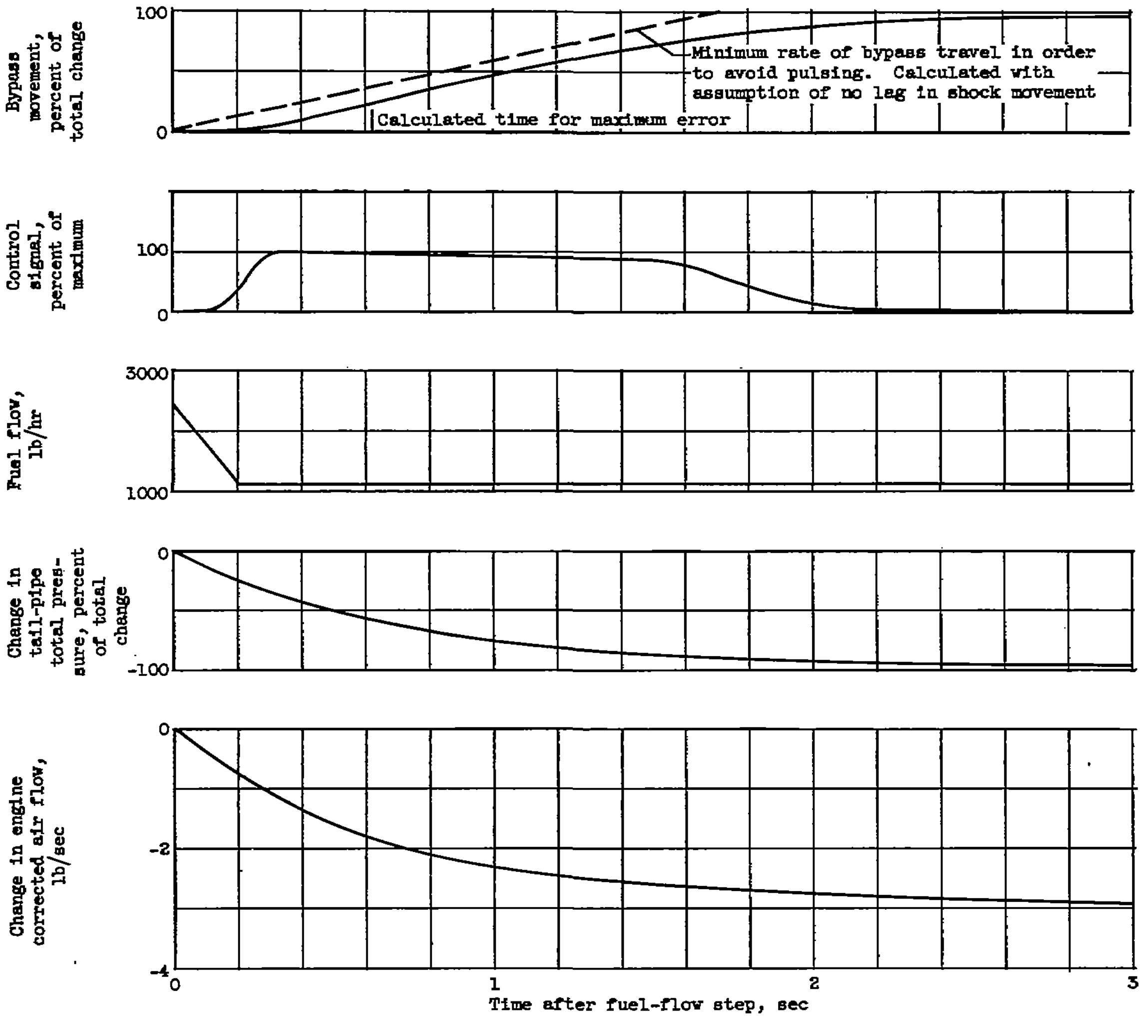

Figure 12. - Response of control at free-stream Mach number of 2.0 to engine fuel-flow change. Sensor gain, 0.0014 volt per pound per square foot (minimum required in order to avoid pulsing).

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